Putting knowledge to use

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> I want to tell you something my brother David, may he rest in peace, once said to me. He said it is as important to learn the important questions as it is the important answers. It is especially important to learn the questions to which there may not be good answers. (Potok, 1986, pp. 295–296.)

Questions about how people learn so that they can use their experiences productively and creatively when facing new situations are at the heart of psychology and education. These are questions about the *transfer problem*. But these questions have not been met with good answers—if by good answers we count those that would have enabled us to formulate designs of learning activities and environments that promote appropriate knowledge transfer. Are good answers available? And will better questions—addressing broader aspects of the transfer problem than ones about the isolated "cognitive" learner—improve our answers?

Contemplating the needs of education in the year 2020 would give anyone deep pause in thinking about these questions. Perhaps new kinds of interactivity, or organizations of learning and teaching, or representations of knowledge, or views of the learner might fundamentally improve the state of knowledge transfer achieved through educational practices. Although many new worlds will be technically possible, can we begin to say what features of specific possible worlds might actualize the transfer of learning so long desired?

I believe we are beginning to gain new insights into the problem of knowledge transfer. These insights have as much to do with recognizing the impacts of the sociocultural organizations of activities in which learning takes place as they do with psychological findings from research on learning. To make our

way to these insights, and toward the goal of framing promising directions for educational technologies, I first need to set a historical context for studies of transfer.

To anticipate somewhat, I plan to develop an *interpretive perspective* on the transfer problem. This is markedly unlike the preeminent theory of transfer whose likelihood is defined in terms of "common elements" of the situations of knowledge acquisition (encoding) and application (retrieval). The interpretive view considers the "appropriate transfer" desired as a product of education to be primarily a sociocultural rather than an objective concept. Elements of previous and current situations perceived to be the "same" by a thinker are not intrinsic in the nature of things but "read" in terms of the thinker's category system of problem types. Such a category system is influenced by culture in significant ways.

I first critically synthesize research findings from the cognitive sciences, especially on studies of learning and thinking in situ, and then identify specific features of thinking-skills instruction likely to be effective for promoting transfer. These features include learning about and practicing knowledge application in multiple contexts of use, constructively participating in bridging instruction across school and nonschool problem situations, thinking and self-management ("metacognitive") skills taught within domains, and synergistic integration of learning for different subject domains. Recommendations are then made for developing new learning technologies that build on these conditions for enhancing knowledge transfer.

WHAT ARE THE DIMENSIONS OF THE PROBLEM?

Knowledge transfer is a problem with many faces at the heart of learning and education. It is not only an individual achievement but a cultural problem, encompassing the study of history and its uses. And education as an ideological institution is itself the attempt to transfer knowledge from the culture to the individual. The interpretive or sociocultural perspective on knowledge transfer developed here is designed to accommodate to these complexities.

The knowledge transfer question is most commonly described one-directionally and thus incompletely: How can formal educational knowledge, acquired in the specialized setting of schools, be transferred appropriately to everyday life and work situations? These observations lament common evidence from the workplace, home, community, and from educators' reports, that wisdom acquired formally is not applied as desired outside the schooling context.

From a developmental perspective, we must ask the inverse question. How can formal education ensure use in its settings of the concepts, skills, and strategies that students have acquired or invented and applied effectively already in everyday life and work situations?

Yet another direction of transfer of skills, strategies, concepts, and other knowledge is transfer between the traditional curriculum divisions. Greater curricular synergy is needed so that students may learn and apply knowledge in an integrated manner matching the demands of everyday situations—in which, for example, writing, reading, mathematics, and science may all come to play at once, not during different class periods, much less organized by textbook chapter boundaries.

The crowning direction of transfer is so widespread that it blurs with the very concept of learning: Transfer studies have been used as a means for assessing learning. If students only can solve specifically instructed problems, failing to solve related ones, we do not attribute subject mastery to them.

Any comprehensive theory of knowledge transfer for education will need to encompass these multiplicities.

Knowledge Transfer and Tomorrow's Education

I first examine several influences that have served in highlighting attention to the knowledge transfer problem. Although specific concerns for educators may vary between now and 2020, the transfer problem has been a perennial one. Thousands of years ago the Greek Heraclitus told us that *we never step in the same river twice*, that every event experienced is in some measure unique. The existence of vast computer data bases of text and images, accessible through easily navigated graphical browsers, with search tuned to one's interests (Weyer & Borning, 1985) will not erase these deep theoretical problems or the practical concerns of the transfer problem. Nor is it clear what would be meant by saying that knowledge transfer will become *more* important in future decades—unless one believes that the more knowledge that civilization accrues, the more intransigent the transfer problem becomes. Access to pertinent knowledge for transfer was already vexing and the subject of satirical humor in the writings of Washington Irving, long before the "information explosion" of the mid-20th century.

There is a widespread anxiety, expressed at teacher educator and subject-matter specialization conferences and journals, about the irrelevancy of much of today's curricula, largely derived in their topical divisions and sequencing from 19th-century curriculum theory, and dominated by fact-oriented learning devoid of knowledge application. Such curricula clash with an information age where the basic facts are changing rapidly, where information is stored and conveyed digitally, and in which the "basic knowledge" citizens need is under debate in most curricular fields because computers are capable of carrying out mechanical aspects of problem-solving activities, as in symbolic equation solving in mathematics, or plotting and transforming graphs.

One response to this contemporary fear has been met with grass roots movements initiated by educator organizations to teach "thinking" and "prob-

lem-solving" skills. Many curricula with this orientation have largely been developed and taught independently of course content. This approach has led to extreme critical reactions, charging that educators have thereby degraded what students know when they graduate (Hirsch, 1987). From a research perspective, it has become quite clear that transfer of learning with such materials to either valued school outcome measures or to enhancing the quality of everyday life problem solving and action has rarely been evaluated (Chipman, Segal, & Glaser, 1985; Resnick, 1987; Segal, Chipman, & Glaser, 1985). But as we see, in the sections that follow, few cognitive theorists recommend instruction in cognitive skills without substantial content knowledge emphasis.

A third contribution to transfer-problem awareness among cognitive scientists came from comparative cross-cultural studies in the 1960s and 1970s designed to test the cognitive consequences of formal schooling and of literacy. Bruner (1966) had suggested that the decontextualized nature of school thinking, such as mathematical reasoning with symbols and equations, and multiple classificatory schemes for their own sake, fosters abstract thinking and formal operational thought. But contrary to expectations, extensive research generally revealed meagre connections made between what was learned in school and other everyday life problem solving (see review by Laboratory of Comparative Human Cognition, 1983).

A fourth influence came from studies by cognitive scientists and science education researchers revealing that even university physics students tend to regress from Newtonian theory toward mistaken physical explanations based on informal experiences with moving objects. Shaken from the frame of their textbook explanations, they resort to nonformal qualitative explanations fraught with inconsistencies (diSessa, 1983). Shweder (1977) presents similar findings for statistical reasoning among presumably statistical literates. Practical cognition is not, it appears, very affected by instruction in formal science or mathematics. Some consider the external validity of much school "learning" questionable if it does not impact on students' practical cognitions.

A fifth, broadly based influence is the belief not only throughout the United States but in foreign educational rationales from Belgium, China, France, Great Britain, Japan, the Netherlands, and Sweden, among others, that learning computer programming will condition the mind to think systematically, precisely, planfully, and more rationally in contexts beyond programming. The current instruction of over several million American students in programming each year is in part a measure of the depth of educators' commitments to this expectation. (As writings by Soloway, this volume, and DiSessa, this volume, make evident, the instructional payoff of "programming" per se will be hard to assess, as trends toward domain-specific programmable tools and activities become realized, and learning to think procedurally—the real breakthrough of programming, Sheil, 1981—becomes integrated within diverse disciplines.)

Although incomplete, this list of contributing factors to the present level of attention in the research and educator communities to problems of knowledge

transfer attests to the diversity of influences at work. The historical roots of the dominant theoretical perspective for transfer of learning now require some illumination.

"What's the Same?": Thorndike's "Common Elements" Transfer Theory

Early in the century, Thorndike carried out many learning transfer studies to test William James' (1890) hypothesis on the specificity of learned habits. It was then common for students in school to learn Latin, not so much for its utility as for its anticipated general promotion of "mental discipline" for learning other curriculum topics. The negative findings from these investigations (Thorndike, 1924; Thorndike & Woodworth, 1901) devastated the discipline hypothesis and helped open up a period of vocationalism in American schooling (Cremin, 1961). Similar arguments are pressed today for the study of logic, mathematics, and science, but particularly for computer programming. As in the case of Latin, where spontaneous transfer outcomes have been carefully assessed for programming, findings have not been promising (Kurland, Pea, Clement, & Mawby, 1986; Milojkovic, 1983; Olson & Soloway, 1987; Pea & Kurland, 1984). Whereas more guidance and structure may yield more significant transfer results, these findings come from explicitly training for generalizability of specific reasoning skills beyond programming contexts (e.g., debugging; Carver, 1986).

As an alternative to the belief that learning rigorous topics generally disciplines the workings of a young mind, Thorndike and Woodworth (1901) offered a specific transfer theory based on the idea of identical elements. On this theory, transfer of knowledge or learning will occur between two tasks insofar as the tasks *share* identical elements, particularly perceptual features. Versions of this common element theory have persisted ever since Thorndike's associationist theory came to prominence in education (Brown, Bransford, Ferrara, & Campione, 1983; see Ellis, 1965; Gagne, 1968; Osgood, 1949).

We can now answer, "what's the same?" *Common elements theory* is now common. It is under revival (although often unknowingly, because memories are short for big ideas) in artificial intelligence (AI) theories of transfer of learning, commonsense reasoning, metaphor comprehension, and human–computer interaction. "Elements" today are commonly defined in the knowledge representation programming languages in which such AI reasoning systems are built (Carbonell & Minton, 1983; Winston, 1978, 1979). A common elements approach to transfer also appears in Polson, Muncher, and Engelbeck's (1986) account of learning different word-processing systems.

The units of the transfer metric in such theories differ from the physical or symbolic elements of Thorndike's theory, but the logic of the approach is identical. Instead of common physical elements in situations, theorists now count

as indices of "similarity" either nodes in a knowledge network, or overlapping rules in production systems as a measure of the likelihood and direction (positive or negative) of knowledge transfer.

Access and Availability of Knowledge

Cognitive developmental studies have provided other central findings and concepts for an appraisal of knowledge transfer theory. Numerous investigations in a Piagetian tradition had by the early 1970s documented in excruciating detail the conceptual "inadequacies" and "deficits" of preschoolers. They could not reason causally or arithmetically, could not conserve number, had bizarre ideas about animacy, and so on. But under more clever research designs and observer scrutiny, 2- to 4-year-olds demonstrated they had much greater conceptual, logical, and social understanding than previously acknowledged. How did such inconsistencies emerge?

The secret of the revealing studies resided in the construction of the situations for assessing children's skills or knowledge. Working with familiar materials in familiar settings with simpler (if any) experimental instructions, research thoroughly documented the rich and precocious understanding of the world possessed by the preschooler (Donaldson, 1978; Gelman, 1978; Gelman & Brown, 1986). (These works were likely influenced by comparable studies of cross-cultural cognition [see review in Laboratory of Comparative Human Cognition, 1983] that had "experimented with the experiment" [Scribner, 1977] once they "found" the obviously questionable result that non-Western adults could not reason logically with traditional laboratory-derived measures.)

To understand these contrasting findings, the distinction between *availability* and *access* of knowledge, earlier elaborated for adult memory by Tulving and Pearlstone (1966), is central. Its relevance to the transfer problem in education is that the preschooler had available the requisite knowledge to accomplish the experimental task, but it had not been accessed as it should have been—from the experimenter's perspective anyway—in earlier studies.

Two Types of Transfer

Voss (1987) helps clarify the distinctions and data that cognitive science has brought to bear on transfer. We briefly summarize his observations and introduce related findings as appropriate. Voss considers transfer a more fundamental concept than either learning or memory (cf. Ferguson, 1956). He argues that transfer must be viewed in relation to the individual's prior knowledge that is utilized in the transfer situation. As in Ferguson's (1956) definition, we consider any identifiable covariation between any two or more forms of performance as a transfer function.

The study of transfer in psychology and education therefore requires re-

evaluation of the traditional transfer paradigm, that is, Learn A, Learn B versus Do-Not-Learn A, Learn B. Voss's observation therefore suggests the following distinction: Transfer may be studied by observing performance as a function of prior knowledge, as in the expert–novice paradigm, or transfer may be studied in the traditional training paradigm, bearing in mind that utilization of prior knowledge is nonetheless taking place. Transfer in these two circumstances is now examined. In either case, we already begin to see complications of Thorndike's picture, because learner characteristics (knowledge, expertise) and not only objective features of situations are presumed to influence transfer.

Transfer Involving Utilization of Prior Knowledge

Knowledge utilization is often assessed by comparing how well learners spontaneously transfer knowledge they possess or have recently acquired to a new problem context. Voss, Greene, Post, and Penner (1983) showed that experts in Soviet political science, when asked to solve a problem of poor agricultural productivity, carry out a two-phased problem-solving process. They both develop a problem representation and state and justify their solutions by means of two fundamental processes: *categorization* and *knowledge retrieval*. In categorization, the problem solver acts to link the problem statement contents to known problems, or some more comprehensive principle in terms of its structural rather than surface features (Larkin, McDermott, Simon, & Simon, 1980). Experts' knowledge is considered hierarchically defined in terms of inclusive problem types and tokens, principles and cases, whereas novices create problem representations based on specific concepts found in the problem statement. Scribner and Cole (1973) argued similarly that formal education prepares the learner to consider new problems as class members rather than as unique.

Voss et al. (1983) also found expert–novice differences in knowledge retrieval. If a problem could not be recognized as a token of a known type, experts but not novices used a goal-directed and constrained search in their knowledge retrieval, guided by specific reasoning strategies such as stating arguments, rebutting counterarguments, qualification, analogies, and problem-solving methods like problem decomposition.

Related difficulties have been documented with knowledge utilization transfer from school learning. Early arithmetic and algebra instruction both provide salient examples of failed knowledge utilization from school learning (Resnick, 1987). For either equation transformation rules necessary for algebra equation solving, or the symbol manipulations required for solving written multidigit subtraction problems (Resnick, 1982), students often have great difficulties. They make errors when syntactic operations they carry out with the formal, written system are not connected to actual problem situations—even when these connections could render the written expressions meaningful. Whereas the point of abstract expressions may ultimately be to allow context-free calculations,

the end goal is not a pedagogical recommendation for referentially isolated learning.

Pettito (1985) argues that inappropriate transfer may arise from school arithmetic. Such effects are revealed in Scribner and Fahrmeier's (1982) study comparing the reasoning of dairy workers versus high school students in a series of tasks involving calculations for milkcrate packing. The dairy workers were highly flexible in the arithmetic strategies they used. The high school students were very inflexible: When new practical arithmetic problems demanded revision of calculation strategies for optimization, students continued to apply their school-learned procedural rules.

Resnick and Omanson (1987) have demonstrated through "mapping instruction" that one can provide instructional support for young children's integration of their practical experience in mathematics with school knowledge. Children may display skill in using base-ten manipulables (Dienes blocks) to represent written numbers and carry out matching operations in the two representational media, while nonetheless making errors in manipulating place value in written subtraction and addition problems. The intensive mapping instruction used has the teacher guide the child to link the semantics of the base system with the syntax of the written algorithms. The written form is depicted as marking a record of block manipulations as the children alternate between subtracting the written and the manipulable media. Children with former procedural bugs in written arithmetic did not make errors even 3 to 6 weeks after such instruction. Mapping instruction appeared to have taught children where to look for the links between their practical knowledge of base-ten relationships and the written arithmetic algorithm (Pettito, 1985).

There is a related lack of transfer from invented and everyday mathematics that works to contexts of school mathematics, where performance falters. This was an early finding of Gay and Cole (1967). They showed that Liberian farmers successfully used measurement and calculational systems in areas that affected their well-being in life situations but had little understanding of mathematics as a generally useful abstract knowledge system. And Carraher, Carraher, and Schliemann (1985) recently discovered that young Brazilian children use informally developed counting procedures to solve many arithmetic problems in the marketplace that they cannot solve in school.

Recent ethnographic studies of thinking point to the same results for schooled adults, whose everyday mathematics in practical activities such as shopping, managing money, and dieting (Lave, 1987; Lave, Murtaugh, & de la Rocha, 1984), or loading trucks with dairy orders in the factory (Scribner & Fahrmeier, 1982) works but is not transferred to school tasks such as written mathematics testing. In a related vein, Resnick (1987) notes that many children fail to see that the formal rules taught in school and their own independently invented mathematical intuitions are related.

The sensitive nature of how the thinker *reads* a problem situation as one appropriate or not for transfer of mathematical competencies is revealed in

Lave's (1986) discussion of an experiment by Capon and Kuhn (1979). They attempted to simulate best-buy supermarket shopping outside a store where customers were requested to compare actual pairs of different-sized store containers of a product for a best buy. Lave suggests that subjects' inadequate use of proportional reasoning in the Capon and Kuhn study, which dramatically contrasts with near-perfect performance in her own research group's studies within supermarkets, is due to circumstances in the Capon and Kuhn experiment that reminded subjects of school-learned arithmetic algorithms. Specifically, they asked subjects to write out their work for comparing best buys (process) rather than just selecting the best buy (answer). In reading the situation as one with an activity organization like a school-based task and thus as requiring a particular type of mathematical activity, Capon and Kuhn's subjects did not appropriately transfer the knowledge they (presumably) had available to the problem situation created for the experiment.

This concept of *situation reading* is an important one for the study of knowledge transfer, and it highlights a deep problem in current cognitive theories of transfer discussed shortly.

Transfer Involving Knowledge Use: The Traditional Paradigm

Assessments of knowledge-acquisition transfer provide the paradigm case of educational transfer studies, such as Thorndike's studies on transfer of learning from Latin, or Polson et al.'s (1986) studies of how learning to use a first word processor affects the ease of learning to operate a second one (for reviews of extensive research with this paradigm during the heydays of "transfer of learning" studies, see Gagne, Foster, & Crowley, 1948; Ellis, 1965). Voss (1987) observes that this classic transfer paradigm involves superimposing the transfer instructional treatment (such as Latin, or a programming language; Pea & Kurland, 1984) on the subject's existing knowledge base. Thus, one needs to know how preinstructed knowledge influences subsequent learning. Voss suggests that classical studies of transfer (and, we may add, studies of programming's cognitive effects; Kurland, Pea, Clement, & Mawby, 1986) may yield nonsignificant effects because the new learning is unimportant relative to the influence of prior knowledge in transfer task performance.

This *constructivist* perspective—the conception that learners build new understanding in terms of prior concepts or conceptual systems—has perhaps become most apparent in the case of science learning (Driver, Guesne, & Tiberghien, 1985; Hawkins & Pea, 1987; Linn, 1986; Osborne & Freyberg, 1985; West & Pines, 1985). The widespread finding is that preinstructed knowledge provides a conceptual foundation that instructional processes must meet through diagnostic activities and then build on. The key notion is that the learner's prior knowledge is *generative*, used in an attempt to understand the new in-

formation offered by instruction. In the terms of Bransford and Franks (1976), such prior knowledge structures "set the stage" for comprehending what goes on in school, relating that experience in terms of the past but allowing for the articulation of unique aspects of the new situation.

One of the principle ways in which prior knowledge may influence transfer task performance is by means of categorization processes. Insofar as education can promote the formation of appropriate categories of problem types, transfer is supported when a categorization process is used to subsume a new problem under a known type, and an attempt is made to apply prior knowledge about successful strategies for dealing with that type to the present case.

Data bearing on this hypothesis is available from cross-cultural studies of the cognitive consequences of formal schooling. Scribner and Cole (1973; also see Cole, Lave, & Sharp, 1979) found that schooled students were more capable of transferring problem solution methods learned early in a problem sequence to different but related problems than were nonschooled students. But as Pettito (1985) cautions, because the tasks in those studies were all school problems, generalization of learning to practical activities remains an open empirical question.

Relation to Analogical Reasoning

A psychology of *analogical reasoning* is fundamental to an understanding of the knowledge transfer problem (Carbonell, 1983; Gentner, 1983; Holyoak, 1985). The reason is that analogical mapping is a process of recognizing the similarities between a past situation x (source) and current situation y (target), and then using details of one's memory of x to structure and elaborate one's understanding of y. Such analogical mapping consists of transferring information from the source to the target domain. The success of this process requires: (a) that the thinker has rich knowledge of the source domain that is applicable to the target (supporting Voss's claim that an understanding of the prior knowledge base of the thinker is essential to an analysis of transfer), and (b) that there is no radical translation problem between the conceptual schemes of the learner for the source and target domains.

But similarity comparisons of source and target domains may be simplistic: Because novices do not understand the target domain, mapping appropriately onto it may be quite difficult (Carbonell, 1983; Carey, 1986; Ortony, 1979; Schank, 1986).

The Dimensions of Transfer Redefined

The development of intelligence has long been defined as a shift from context-dependent knowledge use, where knowledge and skills resources are "welded" to their initial context of acquisition, to more context-free generalizations of

the use of intellectual resources. In this sense, the lack of transfer of learning to new contexts was equated with rigid intellectual functioning, or "mechanization" (Luchins & Luchins, 1959).

But it has rarely been alleged that to transfer knowledge indiscriminately to new situations is a hallmark of high intelligence. More is involved in the transfer problem than transfer in terms of "common elements" regardless of circumstance. *Selective* knowledge transfer, that is "appropriate," which "works," defines the valued outcome of thinking and action. In this section, different dimensions of the knowledge transfer problem are sketched to resituate it as the cultural and interpretive problem it is.

In the cognitive science renderings of the knowledge transfer problem described earlier, the learner is alone and a "cognitive" being. But accounts of transfer restricted to the individual and to only cognitive aspects of transfer must be considered a theoretical legerdemain. Other influential dimensions of the problem involve basic concerns about the sociology of knowledge use and acquisition, anthropological and cross-cultural issues about the interpretation of situations for thinking and learning, and how motivational and attitudinal states may affect the likelihood of transfer.

Important questions arise about the *purposes* of knowledge transfer, and to the related *values* issues lurking beneath the surface of the concept of "appropriate transfer." Because desired transfer is selective, where do the selection principles come from? If we address only the conditions of learners' knowledge states, which causally incline them to knowledge transfer ("cognitive mechanics"), we will fall short of explaining the selectivity of transfer. We are reminded of Dilthey's (1833/1976) insightful remark that "no real blood flows in the veins of the knowing subject constructed by Locke, Hume, and Kant; it is only the diluted juice of reason, a mere process of thought" (p. 162). Insofar as a cognitive mechanics is possible, it will only be likely to suffice for a highly restricted set of knowledge use and acquisition situations. As Skinner (1971) once observed, "the world of the mind steals the show" (p. 12).

Writers often mention "appropriacy" of knowledge transfer but not the social construction of such categorizations. According to Papert (1980, cited in Dreyfus & Dreyfus, 1986) "true computer literacy is not just knowing how to make use of computers and computational ideas. It is knowing when it is appropriate to do so" (p. 122).

"Inappropriate" transfer (often called "negative") refers to cases when one has transferred prior knowledge and "should not" have. But observe that such negation is not epistemic, defined in the nature of things, but deontic, defined in the nature of social meanings. Such prescriptions reveal that "appropriate transfer" is not a natural kind, but defined by cultural and individual value systems. Particular transfers of learning from the learning context to a new situation are never intrinsically "appropriate," but only as judged against a set of conventions reflecting the values of the culture to which the learner belongs (Shweder, 1986).

A continuum of four cases conveys the spectrum of conventions that enter into judgments of the appropriacy of transfer. The child overgeneralizes a lexical term, calling any cloth a "towel" that is wet from a spill. He has confused the incidental and vital features of "towel" because his first acquaintance with the term was with a wet cloth. Judged from community standards, this is inappropriate transfer. But from the child's perspective, these naming tasks share certain "common elements."

In our second case, the grocery shopper who has learned the decision analysis method of multiattribute utility theory in her thinking-skills course applies it to the decision problem of picking a tomato at the greengrocer for making a pasta sauce. She explicitly defines the various criteria that matter to her for judging tomatoes, weights their importance, and evaluates each tomato option by each criterion. Several hours later, after lengthy calculations, she optimizes and selects the best tomato. Whereas we would deem this transfer of a higher order thinking skill inappropriate, because the effort expended is disproportionate to the seriousness of the decision problem, the same approach would be appropriate if the task were diamond selection by a gemstone carver for the queen's tiara, or a site for a new missile silo.

Similarly, the military strategist may think that because people can be counted like objects, they are like objects, subject to cost-benefit analysis, and thus minimizing body counts is a desiderata in battle planning. Depending on one's value theory, this may be considered highly "inappropriate" transfer. Similar cases could be detailed in risk analysis for nuclear or toxic waste disposal, insurance risk assessments, and other science-technology-society problems.

Finally, to take an extreme case, if one taught burglars to define goals, to plan and to do progress monitoring, and to use precision in their thinking, these skills would very likely be transferred to their clandestine thievery work. Such transfer is channeled toward the purposes such individuals consider relevant to their life space. But the burglars' purposes are negatively valued goals for transfer from a prosocial perspective, and deeply inappropriate.

Common Elements as Social Constructions

Hoffding (1892) brilliantly argued against Thorndike's seminal treatment of transfer, urging that the issue is not, as Thorndike supposed, one of measurable physical elements of problem environments, but of the learner's construal of task domain similarity. Although physical similarities can influence likelihood of transfer, *perceived similarity* is fundamental. What matters is how the new situation reminds the thinker of previous situations, which is liable to be quite idiosyncratic.

In this respect, Hoffding's approach is congruent with Dilthey's 19th-century work on "moral sciences" such as history, psychology, sociology, literary criticism, and "hermeneutics," the interpretive methodologies humans apply to under-

standing the meaning of situations and social phenomena as if they were texts. Similarly, Dewey (1922, p. 131) critiqued psychologies such as Thorndike's that assume that the lists and categories they construct represent fixed collections *in rerum natura*, when lists serve only as classifications for a purpose.

Unfortunately, anthropological study of perceptions of contexts for transfer of learning has been minimal until recently. In contrast, societal influences on the selective principles controlling attention have been a concern linking psychology and anthropology since early in the century (e.g., Evans-Pritchard, 1934; Wilson, 1970). Studies rooted in Marx's observations on this topic were carried out, with special attention to thinking in non-Western cultures, by Durkheim and Levy-Bruhl in France, and by Bartlett, Evans-Pritchard, Malinowski, Rivers, and Radcliffe-Brown in England. For example, as Evans-Pritchard (1932) stated:

> As James, Rignano, and others have shown, any sound or sight may reach the brain without entering into his consciousness. We may say that he "hears" or "sees" it but does not "notice" it. In a stream of sense impressions only a few become conscious impressions and these are selected on account of their greater affectivity. A man's interests are the selective agents and these are to a great extent socially determined for it is generally the value attached to an object by all members of a social group that directs the attention of an individual towards it. It is, therefore, a mistake to say that savages perceive mystically or that their perception is mystical. On the other hand we may say that savages pay attention to phenomena on account of the mystical properties with which their society has endowed them, and that often their interest in phenomena is mainly, even exclusively, due to these mystic properties. (p. 24)

More recently, Cole and colleagues at the Laboratory of Comparative Human Cognition (1979, 1983, 1984) have critically reviewed contributions of developmental and cognitive psychology, anthropology, and sociology to the understanding of how individuals in a culture come to acquire belief systems that specify how experienced events are connected. They argue for a "cultural practices" theory (1983), according to which the kinds of social contexts children participate in contribute to the fundamental categories of experience out of which cognitive development and knowledge transfer arises. These contexts are not defined in terms of physical features of settings, but in terms of the meaning of these settings constructed by the people present. Such an interactional conception of cognition in culture provides an important foundation for investigating the dimensions of the knowledge transfer problem in education.

In the case of current cognitive theories of transfer, this question of interpreted rather than objectively given "elements" serving as the basis for transfer is begged. The productions in production systems modeling human thought or the nodes in knowledge representation networks in cognitive simulations are part of the *theorist's* construction of the problem situation. The question is begged because the problem-solving context is interpreted, not an experimen-

tal variable defined invariantly across subjects. If it were so simple, findings of "no transfer" in experimental studies of problem-solving strategies would not be so common. The elements of situations said to determine the suitability of transfer are treated as reified entities rather than as socially constructed, situated realities. It seems likely that using an interpretive approach to the problem of selective knowledge transfer will offer a more productive orientation to educational activities design for promoting transfer than the traditional common elements one.

It is perhaps not surprising that the renowned cognitive studies that fail to find transfer of problem-solving strategies involve puzzle problems such as the Tower of Hanoi and Missionaries and Cannibals, which are "formally identical" (in terms of the problem-solving operations required for their solution) but have different "surface structures" (Reed, Ernst, & Banerji, 1974; Simon & Hayes, 1976). Note here that the "common elements" between such problems are not physical problem features as in Thorndike's initial formulation of transfer theory, but problem-solving production rules. In terms of the important role of problem categorization on transfer likelihood, why should the college student in such studies have seen those puzzle problems as belonging to the same type? They were not taught or discussed as a class of problems of similar type; it is only at an abstract level of analysis that they are formally identical. The same point applies to Gick and Holyoak's (1980, 1983; also see Perfetto, Bransford, & Franks, 1983) work on transfer of problem-solving solutions from a divide-and-conquer battle story, to Duncker's radiation problem and related problem analogs. In each case, subjects had to be prompted that information given to them was relevant to solving the problem posed, for without the prompt they did not use the information.

Need for a Cultural Practices Framework

How do socially organized activities come to have consequences for human thought? No clear theory of the mechanisms by which the social affects cognitive variation is available. But recent theory influenced by Vygotsky's (1978) cultural-historical theory of higher mental functioning suggests one promising direction. Scribner and Cole (1981) have provided an important framework, developed in over a decade of cross-cultural cognitive research, for thinking about how "cultural practices" influence thinking. Rather than focusing on the features of a technology (e.g., formal schooling, written language) alleged to influence cognition, they approach a set of practices, such as literacy, as a "set of socially organized practices which make use of a symbol system and a technology for producing and disseminating it" (p. 236). "Practice" involves technology, knowledge, and skills. It is defined as a particular technology and a particular system of knowledge. "Skills" are the coordinated actions involved in applying this knowledge in particular settings. This framework on cultural practices has

dramatic consequences for conceptualizing transfer: "Literacy is not simply knowing how to read and write a particular script but applying this knowledge for specific purposes in specific contexts of use. The nature of these practices, including, of course, their technological aspects, will determine the kinds of skills ('consequences') associated with literacy" (p. 256).

In terms of their framework they can make sense of results of their careful studies on the cognitive consequences of literacy in relation to those of schooling, which documented an asymmetry of schooled and nonschooled literacy effects. School and nonschool contexts for using literacy skills involve different tasks, even for the "same" practice of reading and writing. The most profound effects of schooling were found for experimental tasks requiring verbal explanations for why a problem was solved in a particular way. They suggest that the skills required in teacher–student dialog practices in the classroom contribute to these distinctive school effects of literacy on cognitive tasks.

An important consequence of the cultural-practice approach to transfer is that because cognitive achievements are largely unique in their contextual characteristics, and yet clear influences of prior learning on present activity are evident, one must "look to the organization of the environments in which interactions occur" (Laboratory of Comparative Human Cognition, 1983, p. 341) and recognize that "transfer is arranged by the social and cultural environment. . . . Overlap in environments and the societal resources for pointing out areas of overlap are major ways in which past experience carries over from one experience to another" (ibid). We presently have little research understanding of specifically how "areas of overlap"—categories of situations on which transfer seems to depend—are socially constructed. How are such categories formed? Through what experiences with discourse on events (their "sameness" or "differentness"), and actions in the material and symbolic environments that a culture has composed?

Several conclusions may be drawn from this perspective. First, we may expect that promoting knowledge transfer in education will depend on more effective arrangement of environments for bridging knowledge utilization across contexts of value within a culture. Second, we may conjecture that the new interactive symbolic environments that can be constructed with computers could dramatically extend a student's experiences of the environments in which available knowledge is viewed as appropriate for transfer. How might technologies contribute to our "societal resources for pointing out areas of overlap" across situations for which transfer is appropriate?

On Transfers "Not Taken"

In any given situation, an individual has a vast storehouse of prior knowledge that could be related analogically to the present occasion. Perhaps the biggest unexplained mystery of cognition is the selection process involved in such choices.

In fact, as the dramatist and literary critic Kenneth Burke suggests, it is often "perspective by incongruity"—the conjoining of concepts in unexpected ways—through which novel insights are derived. Any AI theory that works out transfers based only on "common features" in some explicit representational language is bound to miss the provocative and interesting novel insights that unexpected juxtapositions of concepts can yield. The history of creative thought in science, mathematics, and literature is rife with such cases.

Furthermore, many potential transfers are never contemplated, and not all transfers that the thinker contemplates are actually followed through, either in thought or action.

So why are some transfers "not taken"? Two answers to this difficult question are explored for present purposes: (1) Because they are not "appropriate," (2) because they "take too much effort." The cultural groundings of each are briefly discussed.

Appropriacy of Transfer. Culture dictates constraints on appropriate transfer in its conventions and mores. Sometimes transfer applications are censored because of taboos that vary cross culturally (e.g., on dirtiness, rawness, sexuality, incest). Some potential transfers of knowledge are so incongruous and unexpected that they serve not to illuminate the worlds of science, but the human condition, and its ways of reflecting on itself, as in humor or exotic literature, revealed in writings such as those of Eugene Ionesco, James Joyce, or Jorge Luis Borges. Conceptual disputes between different ideological communities may also center on what particular transfers are appropriate, e.g., whether certain metaphors for how society functions, or how the mind works, or how light behaves are legitimate. Members of such a community may not make some transfers then, because of ideological constraints on their appropriateness.

It is common to read that students need to acquire "skills of analogical thinking," of generating analogical connections from knowns to unknowns as a means of understanding. This crucial "fluency" aspect of intellectual functioning was stressed in the writings of divergent thinking theorists such as Duncker and Wertheimer and is the subject of much experimentation in modern cognitive psychology (e.g., Sternberg, 1985). But that is only half the issue. What is less commonly noted is a complementary evaluative skill that is required if analogical thinking is to support the learning and problem-solving activities of the learner. Not only should the learner be able to productively generate analogies, but the learner should be able to evaluate the utility of the generated analogy for the purposes at hand. In other words, not all analogies are good ones. Most importantly, *the goodness of the analogy depends on the purposes of the analogizing.* Whether the analogical transfer of knowledge is judged to be good depends on who is doing the evaluation and why. The goodness or utility of a transfer depends on the satisfaction criteria for the thinking task.

Halacz and Moran (1982) argue, for example, that in learning about soft-

ware such as word-processing programs, not all analogies are useful, and some may lead to negative transfer and detrimental miscomprehensions. But they tacitly assume learning efficiency as their utility criterion. Many analogies people use are misleading and may, as in electricity, even be deadly if assumed to be true (Gentner and Gentner, 1983). Resnick (1987) notes how overtransfer of taught reading strategies can disrupt reading if overapplied. In the cases of word processing and reading, sociocultural standards provide cognitive control schemata for judging transfer appropriacy. At the other extreme, the impact of objective standards in evaluating whether transfer works is made strikingly evident by the case of electricity.

The cognitive economics of transfer is another complex of factors, too little researched from an educational perspective, that may influence whether contemplated transfers of knowledge are pursued or not. The pervasiveness of the principle of minimal effort in mental as well as physical action is well documented. In relation to contemplated transfers of prior knowledge to the present problem situation, the thinker asks, even if he or she thinks the transfer might work: Is it worth the costs to carry it out? I may project that the mental work of analogical mapping is sufficiently difficult that it does not outweigh the possible benefits I could derive from the transfer.

Evaluations of such simulated mental effort may influence the likelihood of knowledge transfer even when students have availability and access of transfer-relevant knowledge. Such mental-effort conservation is fundamentally cultural because perceived transfer benefits are value dependent. What one considers transfer of learning to be "worth" in one's effort calculations (whether tacit or explicit) is influenced by cultural concerns such as the value of time, and accountability to others. Determination of such costs will in part depend on an individual's idiosyncratic history of costs and benefits for knowledge transfer in what he or she perceives to be similar situations to the current one. To complicate matters, the veracity of one's projections of the likely cognitive effort of knowledge transfer activities is itself probably influenced by the sophistication of one's prior knowledge. One can be more or less accurate in the estimates one makes of how much work will be involved in transfer.

On a related point, diSessa (1983) describes the potency of *phenomenological primitives* (p-prims) in transfer. These are schemata for understanding situations that are purpose relevant for the reasoning one does in one's "niche" of problem-solving situations. Thus, if one has available a set of p-prims for everyday physical reasoning and is then presented with formal physics problems in school, there may be no mapping between the two contexts because of a radical translation problem across the two problem representation systems (see in particular, Clement's 1986 attempts in physics education to fill such gaps with bridging examples).

There are additional issues in cognitive economics concerning broad-scale conceptual change. What is the new value of the formal physics concepts and methods for the physical reasoning I consider important? Is there significant

payoff to adapt my current conceptual schemes with these new ideas? Or do I just learn formal physics as a separate conceptual system with school-linked conditions of application?

Transfer Attitude

Additional influences on knowledge transfer may be introduced. Earlier the distinction was made between one's access to and the availability of knowledge and skills during a problem situation. Critical to the access problem are affective and motivational factors that are ill understood. How students feel about their capabilities of performance in learning tasks can drastically affect their interest not only in knowledge transfer but in learning itself. How is the disposition to engage in persistent memory search for transfer-relevant knowledge in a problem situation influenced by self-efficacy, fear of failure, anxiety, intolerance of mistakes, or other emotional blocks (e.g., Meichenbaum, 1977)?

Research on *achievement motivation* indicates that if children conceive of intelligence as a stable "entity" whose adequacy is revealed through performance, rather than an "incremental" set of skills to be increased through effort, then they are likely to view errors as personal failures and approach problem-solving events not to learn from, but as occasions to look smart or to fail (Dweck & Elliot, 1983). Diener and Dweck (1978) have distinguished "mastery-oriented" and "helpless" strategies for processing failure feedback in problem solving. Brunstein and Olbrich (1985) make an analogous distinction between the action-oriented strategy to go on to new events, and the state-oriented strategy of dwelling on events.

We unfortunately know little about how such different achievement goals arise. Yet the entity view, the helpless strategy, and the state-oriented strategy can all have crippling consequences for learner motivation when the false starts that are inevitably ingredient to learning and knowledge transfer are viewed as failures (also see Papert, 1980).

Sternberg (1985) makes the important observation that, unlike in education, the need to provide positive motivational conditions for transfer of skill training has been well recognized and effectively handled by behavioral psychologists dealing with treatment programs aimed at overcoming obesity, heavy smoking, and drug addiction.

Even such limited findings as these suggest promising research strategies. The sociocultural orientation to selective knowledge transfer outlined here implies that such affective and motivational influences on knowledge transfer are best studied in the cultural systems that give rise to them rather than as traits of individuals. This runs counter to the common treatment in the literature of children as "intrinsically motivated" or not, or the tendency to seek out the characteristics of a software game that cause intrinsic motivation (Lepper, 1985; Malone, 1981).

Toward Solving the Redefined Transfer Problem

Various sociocultural dimensions of the knowledge transfer problem have been acknowledged. What might education do to better provide for the kinds of activities and emphases that will support students in learning for appropriate transfer? Some clues are suggested by psychological research on instruction in thinking skills for transfer.

Generalizable thinking skills can be successfully taught, including problem-solving heuristics in mathematics (Schoenfeld, 1985); word list learning and recall strategies (Belmont, Butterfield, Ferretti, 1982); planning, goal monitoring, and revisionary strategies in writing (Bereiter & Scardamalia, 1986); reading comprehension skills (Palincsar & Brown, 1984); and skills of allocating effort while studying (Dansereau, 1985; Weinstein & Mayer, 1985). What are some of the elements of success in these efforts? Many directly address aspects of Dweck and Elliot's (1983) statement of children's learning difficulties for intellectual tasks (in contrast to physical ones): "children may be less likely to know what they are aiming for [goals], why they are aiming for it [purpose], how to get there [method], and when they have gotten there [evaluation]" (p. 677).

In the next part of the chapter, I summarize arguments for recommendations about how one might foster the development of appropriate transfer of learning from education. A variety of measures are suggested. They include acquiring knowledge in functional contexts, providing multiple-domain knowledge application examples and experiences, creating bridging instruction across school and nonschool problem situations, and integrating subject learning with synergistic design. The higher order goal of creating cultures of transfer thinking in which these measures play enabling roles is briefly characterized.

Where Is Learning Spectacular and Transfer Common?

In seeking to identify features of an effective education, Bransford, Sherwood, and Hasselbring (1985) begin by asking where learning is *spectacular.* It so happens that where it is, one can find remarkable transfer of what is learned. Such spectacular learning occurs in the first 5 years of life. Then children quickly acquire concepts, language, and motor, spatial, and social skills with minimal explicit intervention. They also appear to willfully learn with little obvious effort. And they do so despite lack of knowledge, few available conscious learning strategies, and probable limitations on working memory (Case, 1985). Bransford et al. (1985, November) describe distinctive features of these spectacular learning contexts:

1. Learning takes place in context. Children learn during the first 5 years while involved in culturally meaningful ongoing activities and receive immediate feedback on the success of their actions.

2. Learning is often effectively mediated. Parents, friends, and peers serve not only as models for imitative learning but help the children learn by providing structure to and connections between the child's experiences, highlighting task-relevant information in a situation, and establishing continuity to functional learning contexts in which children can come to take over part-activities of a whole problem-solving task (Bruner, 1983).
3. Learning is functional. (1) and (2) together help provide children with an understanding of the functions of information for problem solving. Concepts and skills are acquired as tools with a range of purposes.

To Bransford's description of features of spectacular learning settings, I would add that the functions of new knowledge are not only shown but are also often explicitly stated. For example, successful studies for teaching thinking skills for transfer have been explicit in describing for learners the need for and purpose of these new learning activities, e.g., that they will benefit performance (Bereiter & Scardamalia, 1986; Brown et al., 1983, p. 129f; Palincsar & Brown, 1984; Pressley, Ross, Levin, & Ghatala, 1984; Schoenfeld, 1985). These findings suggest that we should explain to students that the transfer of the knowledge they are acquiring is important and why. Otherwise, student improvement tends to be highly task specific. This technique may be effective because orienting children toward what they perceive as high-value learning goals, regardless of their level of perceived self-competence, leads to mastery-oriented striving (Dweck & Elliot, 1983).

The instructional implication is that one should teach concepts, strategies, or skills in problem-solving contexts in ways that make their functions apparent. Such "functional presentations" and the emphasis on learning-by-doing will make it more likely that the knowledge will be accessed and transferred to new problems. Students are provided with real problem-solving situations (or in some cases, models) that engage the concepts and skills under instruction in situations analogous to their desired targets of application.

The Utility of Multiple Examples and "Bridging Instruction"

Multiple contexts of acquisition and application of new knowledge (e.g., in different problem domains) are important because then the encoding of that knowledge in memory has multiple functions associated with it for future retrieval. Consequently, the likelihood decreases that the knowledge is welded in memory to a specific problem context (Brown et al., 1983; Gagne, 1985). Experimental results from learning studies support this prediction (Cheng, Holyoak, Nisbett, & Oliver, 1986; Gick & Holyoak, 1983; Homa & Cultice, 1984).

Gagne (1985) offers the (by-now familiar) suggestion that learning transfer

is a circumstance influenced by the number of common cues between the learning and transfer situations. Transfer is said to be enhanced if the cues available in the situation in which transfer is appropriate are increased at the time of learning, by linking rules with other concepts, or to a more meaningful context such as a schema. Gagne's account is similar to Thorndike's "identical elements" theory. Even though more "interpretive" in its consideration of situation elements, Schank's theories of dynamic memory (1982) and explanation patterns in reasoning (1986) also take a multiple-cue approach.

There is an added complexity to the recommendation of providing multiple examples in knowledge acquisition for subsequent knowledge transfer. Not just any combination of multiple examples will suffice, and which *range* of examples is chosen, and the *sequence* in which the examples are offered, will probably influence the breadth of selective transfer one will observe students making. Yet very little research has systematically examined desirable characteristics of example selection for maximally appropriate transfer.

Some research suggests that representatives of the natural *variability* of category instances should be captured in examples used for instruction (Elio & Anderson, 1984; Fried & Holyoak, 1984), since a single rule can but rarely express the complex "family resemblances" (Rosch, 1978) among situation category members for which transfer is appropriate.

From another perspective, one case suggests the importance of the sociocultural relevance of the examples offered. Children's native cultural experiences were used as bridging activities in the successful school-based KEEP program of text comprehension instruction with Polynesian Hawaiians (Jordan, 1985).

In contrast, de Bono's (1985) CoRT program to teach thinking skills offers multiple examples. But they are all real-life situations such as planning for holidays or choosing a career, and one considers unlikely the spontaneous transfer of such thinking skills to school topics such as mathematics or language arts. Glaser's (1984; also see Frederiksen, 1984) recommendations that higher-order thinking skills be taught primarily within subject-matter domains appears overly restrictive in the reverse direction.

Until more instructionally-relevant research is available on the issue, it seems reasonable to suggest that a representatively broad range of contexts for transfer, deemed culturally-appropriate, including in-school and out-of-school problem situations, should provide the examples used for instruction. Contrast cases of transfer considered inappropriate should also aid in student's category formation and knowledge representation. It is presently ill understood whether explicitly stating principles or rules or definitions in addition to such positive or negative examples is helpful, or sufficient without examples. The transfer payoff of such explicitness has been shown to vary with subject matter and subjects' prior knowledge (Gick & Holyoak, in press).

Feuerstein, Rand, Hoffman, and Miller (1980) train for transfer of concepts or skills in their precollege thinking-skills program with "bridging." Bridging

involves teaching a general principle and then helping students see how it works in multiple situations, e.g., in semantically rich science or social encounters.

Bransford, Stein, Arbitman-Smith, and Vye (1985) discuss how Feuerstein's program, principally used with children with learning difficulties, has students create their own examples and evaluate the adequacy of the examples others offer. These bridging activities have four rationales: (1) They prompt students to draw on their own experiences; (2) they restrict the potentially infinite range of application of principles of the students' life experiences; (3) students' generating examples serves to diagnose their understanding; and (4) instantiating the principle in a variety of contexts encourages transfer. Brown and Campione (1981) describe this approach as explicit instruction in the *range* of knowledge applicability. The assumption is that this instructional strategy will encourage access of transferable knowledge and skills in the future.

Bridging is only one small part of the transfer problem, however. Perhaps more difficult as an educational barrier to promoting transfer is the problem of radical translation between two different situation-perception systems: the child's—derived from everyday experiences—and those promoted by the specialized situations of the formal education of schooling. Establishing the appropriate mapping between the familiar and unfamiliar domains in metaphor comprehension is a challenging process.

Although such bridging activities appear promising as an instructional technique for promoting knowledge transfer, little is known about what may be the best ways (given particular purposes) to convey these bridging relations, for example, through knowledge network diagrams, or verbally (as in Feuerstein, 1980), or in terms of multimedia materials such as interactive videodisc (Bransford, Sherwood, & Hasselbring, 1985).

But conflicts exist between this approach and influential proposals of why schooling has powerful consequences for cognitive abilities as measured by experimental tasks. Bruner (1966) argued that it is the very removal of everyday life experiences from the formal learning situations of school that makes possible deeper learning for its own sake rather than as a subgoal of practical activity. Lave (1986) suggests that the accepted wisdom is that school must provide preparation for life in context-free terms; as it does, then cross-situational transfer will follow. The specific social organization of knowledge utilization should not, by this classic account, affect its meaning, value, or use. The enhancement of abstract symbolic representations taken to undergird the power of formal reasoning through schooling presumably depends on this detachment from the here and now.

Pettito (1985) suggests resolving this conflict by considering that schooling offers learning of rules and principles for *potential* transfer if appropriate links can be made to practical knowledge. In designing a future education to promote transfer, we will need to synthesize the *abstract* treatment of reasoning considered as the support for transfer of learning, and the *situational embedding* of concept learning in problem-solving activities taken from everyday life. Otherwise,

students may not notice occasions for school-type reasoning outside school settings.

Cognitive Self-Management Skills

From cognitive research in the past decade, we have come to understand in a way we never did before the specific characteristics of thinking that define an independent, directed, effective learner and thinker. Cognitive studies of how experts regulate their mental processes when defining and solving problems, as well as instructional interventions designed to teach and coach general cognitive self-management skills, reveal that such skills do exist, can be taught, and are transferred to new materials and domains of study. Many difficulties that learners have are not due to lack of basic knowledge or to unavailability of relevant problem-solving strategies alone, but to "executive" problems with not managing their mental resources effectively. Recent studies show that learners need to acquire not only problem-solving strategies but self-management skills for autonomously guiding thinking and learning episodes.

Consider that when Belmont and Butterfield (1977) reviewed 114 studies on cognitive strategies instruction, none taught executive, self-management strategies and none achieved transfer of skills taught. Since that time, many investigations have directly taught self-management cognitive skills and found dramatic and maintainable transfer of learning effects (reviews by Belmont, Butterfield, & Ferretti, 1982; Brown et al., 1983). For example, Brown, Campione, and Barclay (1979) taught self-monitoring techniques for estimating test readiness and found learners transferred these new skills from word list learning to prose recall.

Our ultimate goal is for learners to become teacher-independent thinkers, learners, and problem solvers. To this end, students need to learn executive thinking skills, such as goal setting, strategic planning, checking for accurate plan execution, goal-progress monitoring, plan evaluation, and plan revision. Yet we know from classroom studies of reading (Beck & Carpenter, 1986), writing (Bereiter & Scardamalia, 1985), mathematics (Schoenfeld, 1985), and science instruction (Herron, 1971), that the fundamental *executive processes* for controlling thinking and learning processes are under the teacher's control, not the students. The contrast case is the effectiveness of the passing on of control processes in the informal education reflected in apprenticeship relations, as in weaving or tailoring (Greenfield & Lave, 1982).

Schools rarely embark on the necessary fading process in which students take over these executive roles for their own self-regulation. Many learners initially require and benefit from explicit support in managing and guiding the complexities of new cognitive activities. Any teaching that aims to foster complex thinking processes should therefore be developmentally responsive in the following sense; that the prompts or other structures it provides for fostering

the development of thinking should fade as students manifest capacity to handle these processes autonomously (Collins & Brown, in press-b; Rogoff & Lave, 1984).

Integrate Subject Learning with Synergistic Design

Promising directions for promoting knowledge transfer in education so far considered have not dealt with the topic of interdisciplinary knowledge transfer. Yet many school reformers advocate linking the learning of different subject domains for greater knowledge transfer in contexts of application or acquisition. For example, Ohm's law as taught in introductory physics is rarely introduced as a simple proportional function from mathematics (Brown & Greeno, 1984). Bransford, Sherwood, and Hasselbring (1985) call such curriculum initiatives to overcome such unproductive isolations *synergistic design*, in which the whole is greater than the sum of the parts. The goal is to make interlinked learning offer greater yield of understanding than the study of disaggregated subjects.

As a superintendent of schools during the 1870s in Chicago, Francis W. Parker eliminated the prevalent rote teaching methods in favor of an emphasis on having children observe, describe, and understand curriculum topics by building on their everyday experiences. Because of these emphases, John Dewey considered Parker "the father of progressive education" (Cremin, 1961, p. 129). Parker's program was an astounding success as reading, writing, spelling, and arithmetic performance soared. Parker (1901–1902) also developed innovative approaches to interrelating curriculum subjects to make their significance more obvious to the child. Many of his techniques are familiar today, including children's creation of their own stories for reading and writing, the combination of studies of grammar, penmanship, reading, and spelling in the motivating contexts of conversation and writing, and the interweaving of science studies with art, mathematics, and writing in the service of understanding nature through fieldwork and laboratory studies. Dewey's famed Laboratory School took a similar approach, starting with the familiar and continuing to enlarge its meanings with the bounties of artistic, literate, scientific, and workplace cultural experiences.

These historical notes are significant because these special efforts were by all accounts highly successful at engaging children's interests and their transfer of learning across curriculum boundaries and beyond school walls. From the problems of unrelated learning in the different curriculum subjects discussed in recent commission and research reports, a revisitation of methods for linking the knowledge attained in the study of different subjects within school would be worthwhile. Although it is tragic that the problem of cross-curriculum segregation has not changed much in 110 years, we have much more sophis-

ticated understanding than Parker or Dewey did of the component tasks, knowledge structures, and reasoning strategies that could in principle contribute to more integrated subject-domain instruction. And information technologies can be used, as we note later, as integrated problem-solving tools requiring the use of knowledge and skills across curriculum areas.

Creating Cultures of Transfer Thinking

Bridging instruction, teaching that conveys knowledge and skills in functional contexts, the provision of multiple examples of knowledge transfer, synergistic curriculum design—all these activities could contribute to the creation of an educational culture that encourages transfer-enhancing learning and thinking processes. Unfortunately, the *culture* notion is elusive. It is perhaps more comprehensible when used as a descriptive term by anthropologists or ethnographers than as a prescriptive term by educators, psychologists, and technologists. Yet it seems essential to try to understand how to build such communities or cultures, particularly because we have seen how, descriptively, cultural practices seem to be the guiding forces in a student's "reading" of a problem situation as one for which transfer of previous knowledge is possible, or important, or worth the effort.

It is highly significant that when the American Association for the Advancement of Science (1984; also see Cole, 1987) looked at several hundred precollege programs for teaching mathematics and science in which minorities and women performed as successfully as white males, they found the programs shared a number of features. The statistical picture reveals that successful programs were those in which there was vertical and horizontal integration of the school educational setting with community learning. Vertically, there was continuity across the grade levels up through college in the quality and commitment of offerings and educational practices involving these groups. Horizontally, there was parental, industry and workplace, and community involvement that was invested in having the students' mathematics and science learning work. In essence, these successful programs had been able to define a culture that said to students that transfer of learning has real consequences.

Research is needed on how to create such thinking cultures, which I take to be closely related to the goal of creating cultures for selective knowledge transfer. Resnick (1987) has summarized tacit assumptions for characteristics of such environments for learning to think independently: (a) self-directed classrooms (on what to work on; activity scheduling); (b) discussion rather than lecture–recitation classes; (c) small cooperative group emphasis.

Social interactions in which thinking processes are made explicit, or modeled, seem to provide important fostering conditions for learning to think well and transfer what one knows to new problem contexts within a broad domain such as reading, writing, or mathematics (Collins & Brown, in press-b; Palinc-

sar & Brown, 1984; Scardamalia, Bereiter, & Steinbach, 1984; Schoenfeld, 1985). They appear to enhance the "disposition" to think (Resnick, 1987). The use of such techniques in education is said to create opportunities for *Cognitive Apprenticeships* (Collins & Brown, in press-b). It is still unclear what the locuses of such effects are, but in part they may provide a culture for thinking in which such activities come to be seen as valued contributions (Schoenfeld, 1987).

Observation of modeling alone is insufficient. Students need to try out such thinking themselves and subject their own thinking processes to community reaction and supportive critique. In participating in this social "zone of proximal development" (Vygotsky, 1978), a child may better envision the new capabilities he or she would have if only the knowledge the other person had contributed were acquired. These think-aloud activities may also positively alter children's self-concepts, their beliefs in whether their intelligence can be developed or is a fixed entity, and their feelings about anxiety, failure, and other potentially disabling emotional blocks to either the knowledge acquisition or application sides of transfer of learning. Similar methods have been promoted by Papert (1980).

Teachers will also need to learn to understand how to promote a culture for transfer in their classrooms by teaching knowledge in use, concepts as tools for understanding, and transfer of thinking skills as an activity central to the social contract of active learning.

Such changes to classroom interactions may be threatening to authority structures. For in an education that takes conveying functional knowledge in multiple contexts seriously, and which tries to build on prior experiences the child brings to the classroom from the thought and actions of everyday life, the locus of authority in the classroom will have shifted. The primary discourse of the classroom would need to shift from the familiar "Do you know X?" frame (Mehan, 1979), a continual regurgitative role for knowledge with the teacher in authority role, to one in which he or she plays a functional role, instead stressing "Do you know X to do Y?" or "What can you do with X to arrive at Y?" or even "What can you make of X?" Uncertainties will arise, which, although epistemologically appropriate (e.g., Hawkins & Pea, 1987), fundamentally change the traditional nature of the teacher's role as all-knowing "Oz" to one of collaborative colleague.

Regular working collaborations between the research community and educators and input to the research agenda on knowledge transfer from teachers will be essential aids to this transformative process. In particular, we will need better methods for helping teachers learn how to diagnose knowledge that students already have from everyday experience, for learning how expert teachers already do this well and how they developed such capabilities, and to refocus and build on such prior conceptions for the purposes of thinking toward which education will be directed.

Roles for Technologies in Promoting Selective Transfer

It is worthwhile asking about possible schemes for using technology to foster appropriate transfer of knowledge in education. Apart from providing new opportunities for process-oriented intervention research on knowledge transfer, as many authors have noted (e.g., Brown & Greeno, 1984), the novelty of computers makes change in the curriculum and in learning/teaching strategies more viable.

There are several directions that appear particularly promising, given what has been said thus far. The general aim is to create tools that enhance the chances that students adopt a self-aware transfer state of mind, and that they be provided with the transfer-relevant access skills and heuristic strategies, and a sufficiently rich taxonomy of problem types for each domain of study to make the application of such search heuristics worthwhile. All the measures I suggest involve the *interpretive* activities of a normative group for a culture (.e.g, teachers, community), whose "situation readings" suggest what transfers are appropriate or not. Such "interpreters" can provide opportunities for students' specific thinking activities to be appropriated into the multiple conceptual frameworks of formal education.

We can also dramatically change the cognitive economics of transfer activities by making the knowledge-application process easier to enact (a common strategy in the design of computer-based cognitive technologies; Bloomberg, 1986). Problem-solving tools could guide the application of prior knowledge, such as equation-solving methods in algebra or composition-planning techniques in writing.

Tools for Building, Linking, and Revising Belief Representations

One approach is to build tools that make it feasible for students to represent the substantive details and connections between in-school and out-of-school thinking experiences, link their within-school experiences across curriculum domains, and revise these structures as aids to belief revision when experience calls for such revisions. In the future, students will be able to construct labeled graphic representations of their beliefs (e.g., as concept network maps; Novak & Gowen, 1984)—but on an electronic whiteboard that would be used to make transfer possibilties to a current problem situation open for discussion or teleconferencing by teachers and other students. Such representations would be available for the student's use in future problem solving, in a sense as a software placeholder of one's conceptual understanding to be built on, and within which new knowledge would need to be integrated. I predict that the

experience of explicitly articulating one's knowledge would render the organization of this knowledge more amenable to retrieval for transfer because it has been given greater structure (e.g., categorical, causal, temporal).

Inquire is a software environment with goals like these under development at the Bank Street College of Education. It will serve as a cognitive technology for structuring and supporting the component activities of whole-task inquiry science by middle school students. Inquiry science includes question and subquestion formulation and cycles of question development, planning of inquiry actions, belief articulation and revision, linking and categorizing notes taken from observational, experimental, and textual research, belief integration in graphical schemes, and the interpretive activities of argument–evidence analysis and scrutiny of quantitative data (Hawkins & Pea, 1987; Hawkins et al., 1987). Annotation facilities of the software will help establish a community of scientific communication and exchange in the classroom, among students and teacher.

Along a more futuristic orientation, and sheerly speculative at the present state of empirical and technical development, would be tools to support "belief revision," building on current research in artificial intelligence on "truth maintenance systems" (e.g., de Kleer, 1986; Doyle, 1984) and "belief maintenance systems" (Falkenhainer, 1987). Some preliminary exposition is required to explain why computer-aided belief revision might be worthwhile to pursue.

Problems of conceptual change are central in cognition, both in the hard sciences and in reasoning toward resolution of so-called "ill-defined" problems of political decision making or design. The major insight of cognitive science research in science learning in the past decade has been that formal science education builds on (or, in the worst case, is acquired in isolation of) a configuration of beliefs about how the world works that is constructed from everyday experience.

Such everyday experience includes not only spontaneous interactions with objects, environments, and persons but socially arranged encounters with informal teaching, memories of explanations offered when questions are asked, and others thinking aloud as they engage in problem solving. These are the resources for the human induction machine of belief formulation.

It is particularly clear that formal science education has paid insufficient attention to students' prior beliefs. Far from being tabula rasas, students come to school with intricate belief systems, often perplexing to the instructor and difficult to ascertain (Osborne & Freyberg, 1985). But the situation is made more difficult because much of science education has bypassed this diagnosis problem altogether, assuming that a well-told story from a curriculum perspective, paying close attention to conceptual prerequisites, and so forth will make for an effective science education. We now know otherwise. Instructional activities should make students' beliefs primary instructional substance. And to serve as primary instructional substance, such beliefs must first be "found." Having been found, learning and teaching activities can then serve—as does

discourse in everyday life—to remediate these conceptual schemes through conversational "repair," so that they can function more adequately for the new purposes of formal inquiry for which scientific reasoning is designed.

What to do about this pedagogical situation is a matter of substantial controversy and empirical investigation. First, how to describe the students' belief states? Positive characterizations are possible of why students have the beliefs they do, because these beliefs may serve them well in the "ecological niche" of problems they have been applying these concepts to, and in the imprecise explanatory accounts they have been required to give of events naturally encountered (Hawkins & Pea, 1987). Such emphases are certainly more pedagogically productive than construals of students as beset with "misconceptions," "faulty theories," etc. So in some important sense, students are "rational agents" in the predictions they make and in the explanations they offer for what happens. Such beliefs are often characterizable as "knowledge in pieces" (diSessa, this volume), not integrated, isolated in "packets" by event types, and easily leading to inconsistent prediction patterns if events for which explanations are required are carefully arranged by the experimenter or teacher in soliciting the student's beliefs.

Some researchers believe cognitive conflicts should be induced by "leading" students to see contradictions that their beliefs produce (e.g., Stavy & Berkovitz, 1980). Some researchers believe that promoting such cognitive "disequilibria" through peer problem solving and debate concerning competing accounts of phenomena is a promising method. Yet others consider that students, like scientists historically (as Kuhn, Feyerabend, and Lakatos show), will only let go of their beliefs and move toward conceptual integration or conceptual change, if a new system of beliefs is offered that works for the problems at hand. The comparative values of such a new belief system may need to be shown "competitively" by way of demonstration.

What all these schemes have in common is that conceptual change is characterized by belief revision. The beliefs an individual has are causally used to provide warrants and evidence for arguments an individual offers for *why* things happen as they do, or *will* (by prediction) happen in such and such a way. Such beliefs are brought forward as parts of explanatory accounts, as premises from which conclusions follow by patterns of reasoning (Toulmin, 1958).

But what does it mean to "revise a belief?" One may modify the conditions in which a belief is considered applicable, one may relate that belief in a new way to another belief or to an outcome, one may redefine the objects of the belief (ontology), and so on. But the important fact about belief revision for the educational technology envisioned is that beliefs have dependency relations. For example, one's beliefs about the predictive power of horoscopes depend on other beliefs about the causal influences of patterns of stars and planets and other celestial bodies at the time of one's birth on patterns of activity during a lifetime. Evidence that forces a revision in the basic belief in such causal

efficacy should also lead to revisions of beliefs that depend on that belief. That is, belief revisions often propagate through dependency chains (de Kleer, 1986; Falkenhainer, 1987).

Whereas it is clear that belief revision is central to conceptual change, and that belief revision should often have global and not only local reorganizational effects on beliefs when evidence so dictates, research on science learning has yet to take a systematic look at the empirical specificities of belief revision, and the nature of constraints on belief revision propagations. This is not surprising. Such analyses are more common and even then have arisen only recently in the field of reasoning by artificially intellient systems. For in constructing such systems, one *has* to be specific. It has primarily been through major contributions to our understanding of the nature of qualitative reasoning in physics that the critical nature of belief dependencies and assumptions has been recognized. Related work on nonmonotonic logic and formal theories of commonsense reasoning provides the logical foundations to these studies. These logics are used to judge cases of reasoning that involve assumptions that may have to be abandoned when new information is made available (Doyle, 1983).

Expert systems that reason to come to conclusions (e.g., about diagnoses of faults in electrical circuits, as would engineers) move through inferential steps based on evidence available to them. How does reasoning effectively about the behavior of the physical world (and devices within it) arise? A major problem-solving technique in AI, embedded in such commonsense reasoning systems, is called *dependency-directed backtracking* (de Kleer, 1986). It aims to evade contradictions in beliefs and is invoked as a process when a discovery is made of a currently inconsistent belief state. This method then changes belief states to eliminate the contradiction, by consulting dependencies (inferences performed in the reasoning history) and records of previous dependencies that the method constructed to deal with previous contradictions.

Consider what might happen if versions of such tools were available for students to use in monitoring belief dependencies and to prompt engagement in belief revision activities. One can imagine students running experiments they have designed to test conjectures they have made, and crafting these in such a way to test a specific foundational belief they have made explicit in a belief representation system. Whereas the learning environment designer would be likely to meet with significant difficulties in creating interactive procedures for soliciting students' beliefs, and in graphically representing belief dependency structures for ready comprehension, research could focus on elaborating and testing interface designs so that students could understand and use such techniques.

Modeling of Multiple Bridging Activities in Thinking

Another use of computer technologies of interest involves making transfer processes *visible*. Successful examples of teaching transferable thinking skills by

Bereiter and Scardamalia (1986), Palincsar and Brown (1984);, and Schoenfeld (1985) all utilize methods for making transfer processes explicit (Collins & Brown, in press-b). For a given concept or cognitive skill, live modeling of its application to multiple cases could be recorded via optical disk storage for a selected range of problems or domains, and where one expects the students to make appropriate generalizations from the cases selected. The system would be highly interactive, enabling levels of help if a student had difficulties in carrying on with new knowledge transfer activities after observing modeling of multiple bridging involving that knowledge.

Reflective analysis of the details of one's own transfer performances as well as those of others should be possible, by replaying problem-solving episodes (Collins & Brown, in press-a). The modeling activities selected would ideally be based on task analyses of knowledge application to the problem situations of everyday life (Sternberg, 1986, offers some suggestions) and bridge these with the problem classes of formal education in mathematics, science, and literacy. The phrase "everday life" is a placeholder for the culturally defined norms of activities that constitute cultural practices.

Ethnographic studies are needed to contribute to a theory of situations, what Scribner and Cole (1981) call *cultural practices*, that help shape what people in a culture "read" as the tasks or problems facing them in a situation. How do these interpreted "common elements" of situations come to be understood or perceived? Are there critically different and intrinsic features of school and nonschool environments that will be important to take into account in designing such bridging activities? If we have answers to these questions, our selection of domains for multiple examples of knowledge application and of methods for introducing them could have more theoretical grounding. Because the everyday life settings found will be likely to vary across cultural groups, cross-cultural cognitive studies will be central to the design of instructional activities supported by the technologies.

The few available tutorial software programs explicitly designed to teach problem-solving strategies fall short when judged against these bridging standards. Examples include *Wumpus*, a fantasy game designed to teach skills in logic, probability, decision analysis, geometry, and *Rocky's Boots*, in which students can use compositions of Boolean logic gates of increasing complexity to build machines that come alive on the screen. In neither case are any links made to in-school topics or out-of-school reasoning situations. As one low-cost measure, such "transfer link" materials could be developed through local school system initiatives and enrich the effectiveness of existing problem-solving software, as Pogrow and Buchanan's (1985) work has demonstrated with compensatory programs for elementary school Chapter 1 students.

Some recent software has begun to address these bridging concerns, such as Sunburst's *Survival Math*. It requires mathematical reasoning to solve real-world problems, such as best-buy shopping, trip planning, and building construction. Efforts to meet these criteria were also taken in creating the Bank

Street *Voyage of the Mimi* materials for mathematics, science, and technology education. In this project (supported by the Department of Education, CBS, Sony, and NSF; broadcast on PBS), video, software, and print media weave a narrative tale of a boat odyssey for whale research taken by young scientists and their student aides. Science problems and uses for mathematics and computers emerge and are tackled cooperatively during the adventuresome activities of the group (Char, Hawkins, Wootten, Sheingold, & Roberts, 1983).

One of the programs from Mimi, *Rescue Mission*, simulates navigational instruments (such as radar, and a direction finder) used on the Mimi vessel, and the realistic problem event of navigating the boat. To effectively work together during this software game, students need to learn how to plan and keep records of emerging data, work on speed–time–distance problems, reason geometrically, and estimate distances. Although none of the software cited directly addresses instruction of generalizable thinking skills or models the processes of knowledge transfer across multiple appropriate examples, each case embodies some appropriate bridging conditions for knowledge transfer.

We are exploring the feasibility of a multiple bridging approach in a software research and development project at New York University called *IDEA* (Interactive Decision Envisioning Aid; Pea, Brunner, Cohen, Webster, & Mellen, 1987). Our goal is to help young adolescents learn elementary decision theory for critical application to school and everyday decision-making situations. In this design, familiar specific domains of decision making—family chore planning, consumer purchasing—are used to introduce generalizable aspects of systematic decision-making skills (such as defining the space of alternative choices, establishing evaluative criteria, utilizing analysis of attributes of alternatives). Multiple examples of applications of these and other general decision-making methods are available through the software, so that at any time the learner can explore or be guided to learn generally useful aspects of methods they are learning to apply in these introductory cases and other situations (such as selecting courses, a high school, or voting for U.S. President). We find that with use of *IDEA*, young adolescents spontaneously identify other decision problems (e.g., party planning, allocating study time, producing a movie) for which they expect such systematic decision methods might improve their decision outcomes. We are now studying whether aspects of such techniques that students can carry out without computer support are used appropriately in subsequent decision making.

Computer Tools and Synergistic Curriculum Design

It should be our high priority to provide a generation of interactive thinking tools for students that can be used across the curriculum. Cross-disciplinary integration of methods and knowledge is the hallmark of problem solving and

problem definition in today's increasingly complex society and world (Hamburg, 1984). But education, particularly in high school, is a collection of disaggregated topics, without any strategy provided for forming appropriate relationships.

With new technologies, we have the opportunity to fit these topics into a context and to help students understand the nature of disciplinary interrelationships and open systems thinking. Even now, such business tools as idea outliners, word processors, data-base-management systems, electronic conferencing systems and bulletin boards, and multimedia electronic notebooks with integrated mathematics–science report-writing facilities are available.

But these systems are by and large agenetic, presupposing that users possess the various thinking skills and task understanding required for their flexible use. There should therefore be an emphasis in the next several decades on creating developmental cognitive technologies—that will have layers of functions associated with students' competencies that learners will shed like skins as they no longer need them (Pea & Kurland, 1987). They should also incorporate easily programmable options so that learners can mold their tools to serve their unique style of thinking and learning (as we are already beginning to see in the macrocapabilities of writing tools, in the "Calculator Construction Kit," and in games such as "Robot Odyssey"). These developmental technologies will also provide approximations to the kinds of task scaffoldings an expert teacher would offer a novice who is learning the system and its relevant tasks. Such support would fade as the student takes on more control of the system's use and displays proficient task performances (Collins & Brown, in press-b).

Cultural Information Transfer Systems

Today one can get to vast quantities of information in Claude Shannon's mathematical sense of the term, but not so easily to meaningful information given one's goals. It is an intriguing thought that it might be possible in decades to come to create information technologies that offer communal "transfer spaces," organized in networks according to topic and even to purpose.

This challenging concern stems from the recognition that future transfer theory should go beyond the level of the individual mind as the locus of study for the transfer of learning to the organization, community, society, and even world levels. The *social distribution of knowledge* and the potentials of interweaving the knowledge networks of communities and organizations with information utilities recommends hard work toward designing *organizational interfaces* for promoting solution of what might be called the *coordination problem* in large-scale knowledge transfer.

Could information technologies be developed to serve as an "information lens" (a concept developed by Malone, Grant, & Turbak, 1986, for the design

of intelligent systems for information sharing in organizations) to focus the yields of others' transfer experiences onto the educational process? How might transfer of learning carried out successfully by others for important cases be used to advantage in an educational system? How should such experiences be stored and accessed? What would it be like to have vast electronic "cultural memories" that have organized for appropriate retrieval and application the prior experiences of individuals within it so that broad gains in transfer to new problems might be made?

Some part of the answer to these difficult questions must lie in classification of problem types, because vertical organization of problem classes is what seems to provide much of the power behind the expert problem-solver's ease in access transfer-appropriate knowledge.

Fortunately, there is research and development work underway on these important questions. Malone and colleagues (Malone, 1985; Malone et al., 1986) have described some of the theoretical and design problems in creating a prototype of an intelligent "organizational interface" for information sharing. Their *Information Lens* utilizes AI concepts such as production rules, inheritance networks, and variable frames but avoids the natural language-understanding problem by offering users a large set of semistructured message templates ("frames"). The initial aim of the *Lens* project is to provide a display-oriented editor system for people to use for filtering, sorting, and prioritizing messages addressed to them, avoiding junk and getting the good stuff. *Lens* has a large number of message-type frames used for composing and sorting messages, and of receivers' interests. Sets of production rules (condition-action pairs) serve as automatic message filters. Defining and using messages and selection-rule types is simplified by their organization in a frame inheritance lattice. In such a lattice network (Fikes & Kehler, 1985), template subtypes inherit field names and property values (such as lists of alternatives, defaults, explanations), and subtypes may have unique fields or different property values. Just as in the case of concepts and words (Miller & Johnson-Laird, 1976), the redundancy of message hierarchies can be exploited economically by inheritance networks to save the effort of entering slightly dissimilar message types anew. (It would seem that a related system of this type might have broad applicability for teacher networking, lesson and activity planning, and other learning-oriented work, such as sharing success and failure stories for techniques that work for particular curricular topics.)

The *Lens* Project and related research and development projects for structured information sharing across electronic communities (e.g., Hiltz & Turoff, 1985; Trigg, 1983) seem to offer promising techniques for the more ambitious kind of information-sharing system proposed here: A Cultural Information Transfer System, the aim of which would be to collect, organize, and disseminate transfer-relevant information and knowledge in forms readily entered and used by individuals. How such a system might be adapted for use in education is too complex a question for analysis here.

Such a Cultural Information Transfer System might even preserve a person's or organization's traces of problem-solving process at an abstract level of analysis, including such details as problem definitions and considered, attempted, and successful mappings of prior knowledge to their current problem situation. These possibilities presume, realistically, that substantial parts of the problem solving will have taken place with computer tools (e.g., financial planning, writing, decision analysis). Wherever an individual has made a mapping between prior knowledge and what they consider to be a new problem, they could register this mapping in the system. Keyword and concept-level "transfer" entry and browsing capabilities would be available for a user's documentation of transfer traces or for directed search through the cultural knowledge traces of knowledge-function relations discovered by others through prior transfer experience and recorded on the system. Individuals could do opportunistic browsing in hopes of being reminded of transfer-relevant knowledge one has, or that one could learn about on the system.

Although considerably speculative in conception, the goal of such a system would be to provide at least an approximate medium of *functional knowledge description and exchange* for aggregating knowledge transfer experience across individuals. Individuals within a culture may have different readings of a problem situation, and the knowledge they each consider as appropriate for transfer application may be different. But at least they share a common language for negotiating the situation's meaning that can then be used to share and critically examine the similarities and differences of their perspectives.

Indeed, it has been suggested that it is *language*, and in particular, descriptions of a task situation across occasions in similar terms, that provides the coding device for capturing a culture's theory of what goes with what—which is then used as a universal resource for organizing an individual's knowledge transfer (Laboratory of Comparative Human Cognition, 1983, p. 341). If this is true, then lexically based information-management systems for aggregating the transfer experiences of a culture, utilizing AI techniques such as those exploited by Malone's *Lens* Project, should ultimately allow for the expansion of the symbolic environments an individual experiences and make more effective knowledge transfer possible.

Conclusions

The analyses of the chapter result in situating knowledge transfer as an *interpretive problem*. We have seen that transfer is not so susceptible to an analysis that reifies "common elements" in problem-solving situations. What observations have led to this conclusion?

The first observation was that transfer is *selective*. "Appropriate transfer" is socioculturally defined for particular purposes, tasks, and thinking situations. When transfer involves more than straightforward knowledge access and ap-

plication, complex personal issues arise of *cognitive economics* (predicting whether knowlege transfer will be worthwhile or not), *analogical mapping* between prior and present situations, and *transfer monitoring* (evaluations of knowledge transfer effectiveness). These judgments are all rooted in cultural practices and value systems.

The second conclusion is that the "elements" perceived by the thinker as common between a past and present situation—on which knowledge transfer appears to depend because of processes of reminding—are not given in the nature of things. They are "read" as texts, with multiple possible interpretations, according to the thinker's culturally influenced categorization system of problem types. Knowledge transfer thus requires *situation analysis*, a determination of the ways in which prior knowledge bears on the situation because the problem reminds the thinker of previous problem cases or types. There are thus likely to be significant developmental, individual, and cultural differences in the *situation perception* on which knowledge transfer depends. These issues have been insufficiently examined in research, and we should place serious attention on them well before 2020.

The implication is that education could positively influence the likelihood of transfer by addressing these problems directly in its practices, and in the technologies it employs. It might do so by making everyday situations and school situations part of the same classification scheme for problem types, by making explicit the links the student is now expected to draw spontaneously, and by checking to see whether appropriate transfers are made. Such a transfer-promoting categorization method could be implemented for many different curriculum topics.

This is not to say such activities will be easy. Extending the sociocultural approach would involve two major steps: Making explicit (in a symbolic representational system such as a semantic network) a student's situational elements for the targeted task setting, and pedagogical activities to help the student transform their belief-structure so that it corresponds with the conceptual scheme promoted by formal education. More instructional attention should go into defining common perceived elements across the spectrum of problems for which transfer of knowledge such as concepts, procedures, or higher order thinking skills is desired. One could then perhaps teach ways of analyzing situations in school with out-of-school ideas and out-of-school with in-school ideas. This bridging should be considered legitimate, even necessary, classroom activity.

The third set of conclusions involves a series of recommendations with the aim of enhancing conditions for knowledge transfer in education. These directions emerge from a critical synthesis of research findings on teaching thinking skills through content. These conditions include learning about and practicing knowledge application in multiple contexts of use, creating bridging instruction across school and nonschool problem situations, fostering thinking and self-management skills taught within domains, and synergistic integrations

of the learning of different subjects. I then pointed to the higher order goal of creating cultures of transfer thinking incorporating these measures and conjectured the likely connection of affective and motivational variables in such an endeavor.

Finally, I sketched what these analyses suggest as promising directions for new techologies that might more directly enhance knowledge transfer than what we see today. Examples included tools for students to use for building, linking, and revising "belief representations" of prior experience in terms of new beliefs acquired through school activities, and interactive systems to help students acquire and practice the application of thinking skills across multiple domains by "live" modeling of multiple bridging activities of new knowledge application. The speculative concept of creating a Cultural Information Transfer System—linking problem descriptions to problem-solving process histories of many individuals and even organizations so that transfer experiences might be broadly shared—deserves closer attention and may be made more feasible by AI techniques.

The prospect of dreaming about education in the year 2020 is a daunting one. We have little reason to believe our visions can begin to touch the possible worlds that may be. Only 30 years ago, behaviorist learning theory reigned, mentalistic terms such as *believe* and *know* were considered taboo in a science of learning, and the filmstrip was the hottest new technology for education. Today we see prototypes of supercomputers with a thousand computers working in parallel, 5-inch optical disks that can store 150,000 pages of text or a full-hour of full-motion video, fiber optics data transmission ready for home installations and for "personal" magazines filtered by interest from newswire and publication services, and personalizable writing and "desktop publishing" systems that can include automatic spelling and syntax checkers, an on-line thesaurus, spreadsheets, graphs, relational data bases, and digitally scanned photographic images. There is a child's doll on the market now that comes with motion, light, and temperature sensors, and which has limited key-word speech recognition ability, all of which are used to cue "appropriate" synthetic speech production; available 64K "insert" cards give her different lexical capabilities.

Given such dramatic changes and the even more rapid trends at work today, particularly in consumer electronics (Pea, 1987), what should we imagine may be available for transfer technologies 30 years from now? In some respects, I suspect it is easy to err in a conservative direction, taking too many present conditions for granted, such as a predominantly school-based education and a predominantly text-based literacy. Cohen (this volume) suggests schools will still be with us. There are some reasons to believe a text-based literacy may not be as dominant as today, as computer screen-based multimedia literacy enters popular consciousness (Pea, 1987).

But what I have sketched seem to me to offer sound orientations for research directions, and for redesigning educational environments—if we desire a more

direct approach to enhancing learning for appropriate transfer in classrooms somewhat like those we see today. The actual embodiments of these ideas will surely be influenced, not only by the winds of technological and scientific innovation in the next several decades, but by the willingness of the complex social structures of educational and research institutions to tackle these intricate problems. We can be sure of one thing: Whatever the specifics may be, it will be a truly exciting period for "putting knowledge to use."

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